

Comparison between the Blue and the Red Galaxy Alignments detected in the Sloan Digital Sky Survey

Jounghun Lee

*Department of Physics and Astronomy, FPRD, Seoul National University, Seoul 151-747,
Korea*

jounghun@astro.snu.ac.kr

Ue-Li Pen

Canadian Institute for Theoretical Astrophysics, Toronto, ON M5S 3H8, Canada

pen@cita.utoronto.ca

ABSTRACT

We measure the intrinsic alignments of the blue and the red galaxies separately by analyzing the spectroscopic data of the Sloan Digital Sky Survey Data Release 6 (SDSS DR6). For both samples of the red and the blue galaxies with axial ratios of $b/a \leq 0.8$, we detect a 3σ signal of the ellipticity correlation in the redshift range of $0 \leq z \leq 0.4$ for r -band absolute (model) magnitude cut of $M_r \leq -19.2$ (no K correction). We note a difference in the strength and the distance scale for the red and the blue galaxy correlation $\eta_{2D}(r)$: For the bright blue galaxies, it behaves as a quadratic scaling of the linear density correlation of $\xi(r)$ as $\eta_{2D}(r) \propto \xi^2(r)$ with strong signal detected only at small distance bin of $r \leq 3h^{-1}\text{Mpc}$. While for the bright red galaxies it follows a linear scaling as $\eta_{2D}(r) \propto \xi(r)$ with signals detected at larger distance out to $r \sim 6h^{-1}\text{Mpc}$. We also test whether the detected correlation signal is intrinsic or spurious by quantifying the systematic error and find that the effect of the systematic error on the ellipticity correlation is negligible. It is finally concluded that our results will be useful for the weak lensing measurements as well as the understanding of the large scale structure formation.

Subject headings: cosmology:observations — methods:statistical — large-scale structure of universe

It has been long suspected that the galaxies may have preferential directions in the orientations of their elliptical shapes (or spin axes) with being locally correlated between the

neighbors, which is often called the galaxy intrinsic alignments. Since the galaxy intrinsic alignments could in principle contaminate weak lensing signals (e.g., Hirata et al. 2007, and references therein), the measurement of its existence and strength from observations has been a prior interest especially of the weak lensing community.

It has been claimed by Mandelbaum et al. (2006) that no signal of ellipticity correlation between the neighbor galaxies was detected in the spectroscopic data from the Sloan Digital Sky Survey (SDSS, York et al. 2000), although they mentioned that their results are statistically consistent with previous observational evidences for the existence of the galaxy intrinsic alignments (Brown et al. 2002; Heymans et al. 2004). Extrapolating their results to redshift $z = 1$ relevant for the weak lensing shear, they have drawn a tentative conclusion that the intrinsic ellipticity correlations between the neighbor galaxies would not cause any significant errors for the estimation of the power spectrum amplitude of the initial density field.

Very recently, however, a numerical analysis based on the high-resolution N-body simulation has demonstrated with high statistical power that strong ellipticity correlations between the dark matter halos exist at large distances out to $10h^{-1}\text{Mpc}$ (Lee et al. 2007). Therefore, it is necessary and important to reexamine observationally the existence and significance of the galaxy intrinsic alignments by analyzing the SDSS data.

The physical mechanism for the generation of the galaxy intrinsic alignments differ between the blue and the red galaxies. For the blue spiral galaxies which are usually rotationally supported, the intrinsic alignments refer to the correlations of the spin axes originated from the initial tidal field. The linear tidal torque theory explains that the intrinsic correlation should exist only locally between close galaxy pairs, whose functional form is predicted to be a quadratic scaling of the linear density correlation function (Pen et al. 2000).

While for the bright red galaxies which are not flattened by rotation, the intrinsic alignments refer to the correlations between the major principal axes of the galaxy’s elliptical shapes which are determined in observations in terms of the anisotropy in their stellar distribution. It has yet to be fully understood what the origin of the anisotropic stellar distribution of the red galaxies is and how it is related to the shapes of the host halos. But the standard model based on the cosmic web theory suggests that it may be due to the anisotropic accretion and infall of materials and gas into the host halo along the halo’s major principal axes which are in turn elongated with the large scale filamentary matter distribution (West 1994; Bond, Kofman, & Pogosyan 1996). Given this anisotropic infall scenario, the red galaxies may have built-in memory of the large-scale filamentary structures and thus their ellipticities might be correlated on larger scales than the spin axes of the blue galaxies.

Even for the blue galaxies, it was claimed that the growth of the non-Gaussianity in the density field would cause large-scale correlations of their spin axes (Hui & Zhang 2002). To account for the large-scale intrinsic correlations between the neighbor galaxies, we use the following formula:

$$\eta_{3D}(r) \approx \frac{1}{6}a_1^2 \frac{\xi^2(r; R)}{\xi^2(0; R)} + \varepsilon_{nl} \frac{\xi(r; R)}{\xi(0; R)}, \quad (1)$$

where r is the three dimensional separation distance of a galaxy pair and $\xi(r; R)$ is the two-point correlation function of the linear density field smoothed on the Lagrangian galactic scale R . Here, the two correlation parameters a_1 and ε_{nl} represent the strength of the small-scale and the large-scale correlation, respectively. If $\varepsilon_{nl} = 0$ and $a_1 > 0$, the galaxy intrinsic correlation will behave as a quadratic scaling of the density correlation function so that $\eta_{3D}(r)$ should rapidly diminishes to zero as r increases, as the linear tidal torque theory predicts. In contrast, if $\varepsilon_{nl} > 0$ and $a_1 = 0$, the galaxy's intrinsic correlation will follow a linear scaling of $\xi(r)$ so that $\eta_{3D}(r)$ should be non-negligible even at large distance.

In fact, we have suggested this formula (eq.[1]) in our previous work (Lee & Pen 2007) to account for the non-Gaussianity effect on the galaxy's spin-spin correlations which are tidally induced. Here we use the same analytic model to describe the intrinsic ellipticity-ellipticity correlations of the galaxies, assuming that since the anisotropic infall of materials that resulted in the ellipticities of the galaxies are also nonlinear manifestation of the tidal field and thus can be approached with the same analytic techniques. Throughout this Letter, the galaxy intrinsic alignments refer to the intrinsic ellipticity-ellipticity alignments of the galaxies, unless otherwise stated.

In practice, what can be measured is the intrinsic alignments not of the galaxy's three dimensional shapes but of its two dimensional shapes projected onto the plane of the sky. According to Lee & Pen (2001), if the two dimensional projection effect is taken in to account properly, the correlation parameter has to be multiplied by a factor of 5/4. Thus, the two dimensional projected intrinsic correlation function is modified from equation (1) simply as

$$\eta_{2D}(r) \approx \frac{25}{96}a_1^2 \frac{\xi^2(r; R)}{\xi^2(0; R)} + \frac{5}{4}\varepsilon_{nl} \frac{\xi(r; R)}{\xi(0; R)}. \quad (2)$$

Note here that although $\eta_{2D}(r)$ represents the intrinsic correlations of the galaxy's two dimensional projected ellipticities, the distance r represents the three dimensional separation. It is also worth mentioning here that for the blue galaxies the intrinsic correlations of the galaxy's two dimensional projected ellipticities are in fact same as that of the galaxy's two dimensional projected spin axes since the spin axes are believed to be orthogonal to the galaxy's major axes.

To measure $\eta_{2D}(r)$ from the real universe, we use a dataset of galaxies at redshift

$0 \leq z \leq 0.4$ downloaded from the SDSS DR6 website (<http://www.sdss.org/dr6/>). A total of 640647 galaxies are found to be in this redshift range. For each galaxy, we obtain information on right ascension (α), declination (δ), redshift (z), position angle (p), major-to-minor axis ratios (b/a), the $u-g$ and $g-r$ colors, and r -band model magnitude (M_r). Among 640647 galaxies, the information on p and b/a are available only for 639727 galaxies, from which we also select only those galaxies with $b/a \leq 0.8$ since for the nearly face-on galaxies with $b/a > 0.8$ the measurements of the direction of their major axes may suffer from large uncertainty. A total of 434849 galaxies are found to satisfy the criterion of $b/a \leq 0.8$.

Using the empirical $u-r$ color separator suggested by Strateva et al. (2001) for the SDSS data, we classify the galaxies into the red ($u-r > 2.22$) and the blue ($u-r \leq 2.22$) sample. Then, we select only bright galaxies by applying the absolute magnitude cut of $M_r \leq -19.2$. Since the SDSS calibration uses the inverse hyperbolic sine magnitudes (asinh) (Lupton et al. 1999), we calculate M_r as the asinh magnitudes using the information on the softening parameter given in the SDSS web site. Finally, we end up having two SDSS samples which consist of a total of 87188 blue and 283972 red galaxies brighter than this magnitude cut of $M_r \leq -19.2$.

For each galaxy, we determine the direction of the major axis, $\hat{\mathbf{e}}$, in the equatorial coordinate system from the given information on p , α and δ : Let us consider two galaxies in a given sample whose major axis directions are found as $\hat{\mathbf{e}}_i$ and $\hat{\mathbf{e}}_j$. First, we calculate the unit projected separation vector as $\hat{\mathbf{d}} \equiv \mathbf{d}/|\mathbf{d}|$ with $\hat{\mathbf{d}} \equiv \hat{\mathbf{r}}_i - \hat{\mathbf{r}}_j$, where $\hat{\mathbf{r}}_i$ and $\hat{\mathbf{r}}_j$ represent the unit position vectors of the i -th and the j -th galaxy, respectively. The separation vectors projected onto the plane of the sky at the position of the two galaxies are given as $\hat{\mathbf{d}}_i \equiv \hat{\mathbf{d}} - (\hat{\mathbf{d}} \cdot \hat{\mathbf{r}}_i)\hat{\mathbf{r}}_i$ and $\hat{\mathbf{d}}_j \equiv \hat{\mathbf{d}} - (\hat{\mathbf{d}} \cdot \hat{\mathbf{r}}_j)\hat{\mathbf{r}}_j$, respectively. Then, the intrinsic correlations of the two dimensional projected ellipticities between the galaxies with separation of r is calculated as

$$\eta_{2D}(r) \equiv \sum_{i,j} \cos^2(\gamma_i - \gamma_j) - \frac{1}{2}, \quad \text{with} \quad \gamma_i \equiv \tan^{-1} \left[\frac{(\hat{\mathbf{r}}_i \times \hat{\mathbf{d}}_i) \cdot \hat{\mathbf{e}}_i}{\hat{\mathbf{d}}_i \cdot \hat{\mathbf{e}}_i} \right]. \quad (3)$$

Here, the angle γ_i represents the direction of $\hat{\mathbf{e}}_i$ projected onto the plane of sky at the position of \mathbf{r}_i . Note that for a galaxy pair with small distance, the quantity $\Delta\gamma \equiv \gamma_i - \gamma_j$ is actually identical to the difference in the position angle Δp . To determine the three dimensional separation distance, r , of a galaxy pair, we assume a flat Λ -dominated cosmology with matter density $\Omega_m = 0.25$, vacuum energy density $\Omega_\Lambda = 0.75$ and Hubble constant $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$ with $h = 1$ (Blanton et al. 2003).

Then, we measure $\eta_{2D}(r)$ for the selected red and the blue galaxies, separately. Then, we compare the observational results with the analytic model (2), determining the best-fit values of the two parameters a_1 and ε_{nl} with the help of the χ^2 -minimization. In the

fitting procedure, the values of the two parameters are confined to $0 \leq a_1 \leq 0.6$ and $0 \leq \epsilon_{\text{nl}} \leq 0.1$ (Lee & Pen 2001, 2007). The unmarginalized errors in the fitting parameters are calculated by the formula given in Bevington & Robinson (1996): The error in the parameter a_1 is found as $\sigma_a = \Delta a_1 \sqrt{2(\chi_1^2 - 2\chi_{\text{min}}^2 + \chi_2^2)}$. Here Δa_1 represents a fitting step-size, χ_{min}^2 is the minimum value of χ^2 , $\chi_1^2 \equiv \chi^2(a_{10} + \Delta a_1)$ and $\chi_2^2 \equiv \chi^2(a_{10} - \Delta a_1)$. where a_{10} is defined as $\chi_{\text{min}}^2 \equiv \chi^2(a_{10})$. The unmarginalized error σ_ϵ in the parameter ϵ_{nl} is also calculated in a similar manner.

For the analytic model (eq.[2]), we use the Λ CDM power spectrum given by Bardeen et al. (1986). For the Lagrangian scale R of each galaxy, we first calculate the luminosity L of each galaxy from its absolute r-band magnitude and then convert it to the galaxy mass scale using the relation of $L \sim M^{0.88}$ (Vale & Ostriker 2006). Then, the Lagrangian galactic scale R is found as a top-hat radius that encloses the mean mass \bar{M} averaged over the galaxies of each sample. When we calculate the absolute magnitude of each galaxy, no K -correction is considered: If our goal were to investigate how $\eta_{2D}(r)$ changes in narrow absolute magnitude bin, then it would be necessary to determine M_r accurately by considering the K -correction (Wake et al. 2006). However, our goal here is rather to measure the average $\eta_{2D}(r)$ for those galaxies which are brighter than a single magnitude threshold in the redshift range of $0 \leq z \leq 0.4$. Hence, a maximum 20% error that may be caused by ignoring K -correction in the estimation of the galaxy absolute magnitude should not be an issue here.

Fig. 1 plots the observational results of $\eta_{2D}(r)$ from the red and the blue galaxy sample as solid dots in the top and the bottom panel, respectively. In each panel, the solid line represents the analytic model with the best-fit correlation parameters a_1 and ϵ_{nl} . The errors are calculated as standard deviation for the case of no correlation as $\sigma_\eta = 1/\sqrt{8n_p}$ where n_p is the number of galaxy pairs belonging to each bin (Pen et al. 2000). As can be seen, clear signals of ellipticity correlation higher than $3\sigma_\eta$ are detected from both the red and the blue galaxy samples at the first bin ($r \leq 3h^{-1}\text{Mpc}$). Note also that from the red galaxy sample the correlation signal is also detected at the second distance bin ($r \leq 3h^{-1}\text{Mpc}$).

Table 1 lists the best-fit values of a_1 and ϵ_{nl} . The results show a marked difference between the blue and the red galaxy intrinsic alignments: For the blue galaxies, the best-fit values of the correlation parameters are found to be $a_1 = 0.20 \pm 0.04$ and $\epsilon_{\text{nl}} \approx 0.$, which indicates that η_{2D} of the blue galaxies follows a quadratic scaling of $\xi(r)$, as predicted by the linear tidal torque theory (Pen et al. 2000; Lee & Erdogdu 2007). In contrast, for the red galaxies, the best-fit values are $a_1 \approx 0$ and $\epsilon_{\text{nl}} = (2.6 \pm 0.5) \times 10^{-3}$, which implies that η_{2D} of the bright red galaxies follows a linear scaling of $\xi(r)$. This observational result is consistent with the picture that the ellipticities of the blue and the red galaxies are induced by the initial tidal field and the anisotropic infall of materials, respectively.

Before assuring ourselves that the detected signal is real, however, it is necessary to examine the effect of the systematic error in the measurement of the position angles of the SDSS galaxies because the systematic error could cause correlations of galaxy ellipticities that mimic intrinsic alignments. To quantify the systematic error, we perform two simple tests. First, we shuffle randomly the redshifts of the selected SDSS galaxies in each sample and remeasure η_{2D} one hundred times. For each distance bin, we calculate the mean averaged over these 100 random realizations and the standard deviation between realizations, assuming that these 100 shuffling processes are mutually independent. If the systematic error had a dominant effect, then a correlation signal would not disappear even when the redshifts are shuffled. Fig 1 plots the mean plus and minus one standard deviation as (green) dashed lines. As can be seen, when the redshifts of the selected galaxies are shuffled, the ellipticity correlations between the galaxies disappear, which suggests that the effect of the systematic error on the galaxy intrinsic alignments be negligible.

Second, we measure the ellipticity cross-correlations between the red and the blue galaxies, which is plotted as solid line and compared with the ellipticity correlation of the red (red dotted) and the blue (blue dashed) galaxies in Fig. 2. If the systematic error caused the correlation of galaxy ellipticities, then we would find non-negligible cross-correlations of the ellipticities between the red and the blue galaxies. As can be seen in Fig. 2, however, the cross-correlations are quite weak at the first distance bin, which reassures us that the detected ellipticity correlations of the red and the blue galaxies are not spurious intrinsic.

It is worth discussing the effect of the redshift distortion that we have ignored in our analysis. For the blue galaxies, its mean peculiar velocity dispersion has been observed to be quite small less than 150 km/s on average (Davis et al. 1997). Therefore it is well justified to ignore the redshift distortion effect. On the other hand, for the red galaxies which are observed to have higher peculiar velocity dispersion around 200 km/s (Davis et al. 2003), the redshift distortion effect may cause non-negligible degree of scatter in the measurement of the galaxy separation distance r . Thus, we do not exclude a possibility that the characteristic distance scale for the red galaxy intrinsic alignments and the value of ε_{nl} could be smaller in real space than observed in redshift space.

The key implication of our results for the weak lensing survey is also worth discussing here. According to our results, the degree of the galaxy intrinsic alignments is quite strong for the bright galaxies at redshifts $z \leq 0.4$. Since the galaxy intrinsic correlations tend to decrease with redshift (Lee & Pen 2007), this implies that at $z = 1$ relevant for the cosmic shear survey the intrinsic correlations may be larger than the detected signal of $a_1 = 0.2$ and thus should not be completely negligible. Our results also suggest that when removing close galaxy pairs as intrinsic ellipticity contaminants from the cosmic shear analysis

(Heymans & Heavens 2003; Takada & White 2004), a typical distance scale of a galaxy pair has to be determined with care, since the scaling of the intrinsic correlations depend on the intrinsic property of the galaxies (red or blue).

We conclude that our first detection of a clear signal of the galaxy intrinsic correlations from the SDSS data will be useful for the weak lensing measurement as well as for understanding the evolution and formation of the red and the blue galaxies.

We thank an anonymous referee for his/her constructive report which helped us improve significantly the original manuscript. We also thank B. Ménard for his help in downloading the SDSS data and R. Mandelbaum for useful comments. J.L. is grateful to the warm hospitality of the Canadian Institute for Theoretical Astrophysics (CITA) where this project was planned and carried out. J.L. acknowledges the financial support from the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korean Government (MOST, NO. R01-2007-000-10246-0).

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is <http://www.sdss.org/>.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

REFERENCES

Bardeen, J. M., Bond, J. R., Kaiser, N., & Szalay, A. S. 1986, *ApJ*, 304, 15

- Bevington, P. R., & Robinson, D. K. 1996, *Data Reduction and Error Analysis for the Physical Sciences* (Boston : McGraw-Hill)
- Blanton, M. R., et al. 2003, *ApJ*, 592, 819
- Bond, J., R., Kofman, L., & Pogosyan, D. 1996, *Nature*, 380, 603
- Brown, M. L., Taylor, A. N., Hambly, N. C., & Dye, S. 2002, *MNRAS*, 333, 501
- Catelan, P., Kamionkowski, M., & Blandford, R. D. 2001, *MNRAS*, 320, L7
- Davis, M., Miller, A., & White, S.D.M. 1997, *ApJ*, 490, 63
- Davis, A. N., Dragan, H., & Krauss, L. M. 2003, *MNRAS*, 344, 1029
- Doroshkevich, A. G. 1970, *Astrofizika*, 6, 581
- Heymans, C. & Heavens, A. 2003, *MNRAS*, 339, 711
- Heymans, C., Brown, M., Heavens, A., Meisenheimer, K., Taylor, A., & Wolf, C. 2004, *MNRAS*, 361, 160
- Hirata, C. M. & Seljak, U. 2004, *Phys. Rev. D*, 70, 063526
- Hirata, C. M., et al. 2004, *MNRAS*, 353, 529
- Hirata, C. M., et al. 2007, preprint [astro-ph/0701671]
- Hui, L. & Zhang Z. 2002, preprint [astro-ph/0205512]
- Jing, Y. 2002, *MNRAS*, 335, 89
- Lee, J. & Pen, U. L. 2001, *ApJ*, 555, 106
- Lee, J. & Pen, U. L. 2002, *ApJ*, 567, 111
- Lee, J. & Erdogdu, P. 2007, preprint [arXiv:0707.1611]
- Lee, J. & Pen, U. L. 2007, preprint [arXiv:0707.1690]
- Lee, J. Springel, V., Pen, U. L., Lemson, G. 2007, preprint [arXiv:0709.1106]
- Lupton, R. H., Gunn, J. E., & Szalay, A. S. 1999, *ApJ*, 118, 1406
- Mandelbaum, R., Hirata, C. M., Ishak, M., Seljak, U., & Brinkmann, J. 2006, *MNRAS*, 367, 611

- Pen, U. L., Lee, J., & Seljak, U. 2000, 543, L107
- Strateva, I., et al. 2001, ApJ, 122, 1861
- Takada, M., & White, S. D. M. 2004, ApJ, 601, L1
- Vale, A., Ostriker, J. P. 2006, MNRAS, 371, 1173
- York, D. G., et al. 2000, MNRAS, 372, 537
- Wake, D. A., et al. 2006, MNRAS, 372, 537
- West, M. J. 1994, MNRAS, 268, 79
- White, S. D. M. 1984, ApJ, 286, 38

Table 1. The redshift range (z), a total number of galaxies (N_g), the range of the absolute magnitude (M_r), the best-fit-values of the linear and the nonlinear correlation parameters.

Color	z	N_g	M_r (no K -correlation)	$a_1 \times 10^1$	$\varepsilon_{\text{nl}} \times 10^3$
Red	[0.0, 0.4]	283972	≤ -19.2	0.0 ± 3.1	2.6 ± 0.5
Blue	[0.0, 0.4]	87188	≤ -19.2	2.0 ± 0.4	0.0 ± 1.6

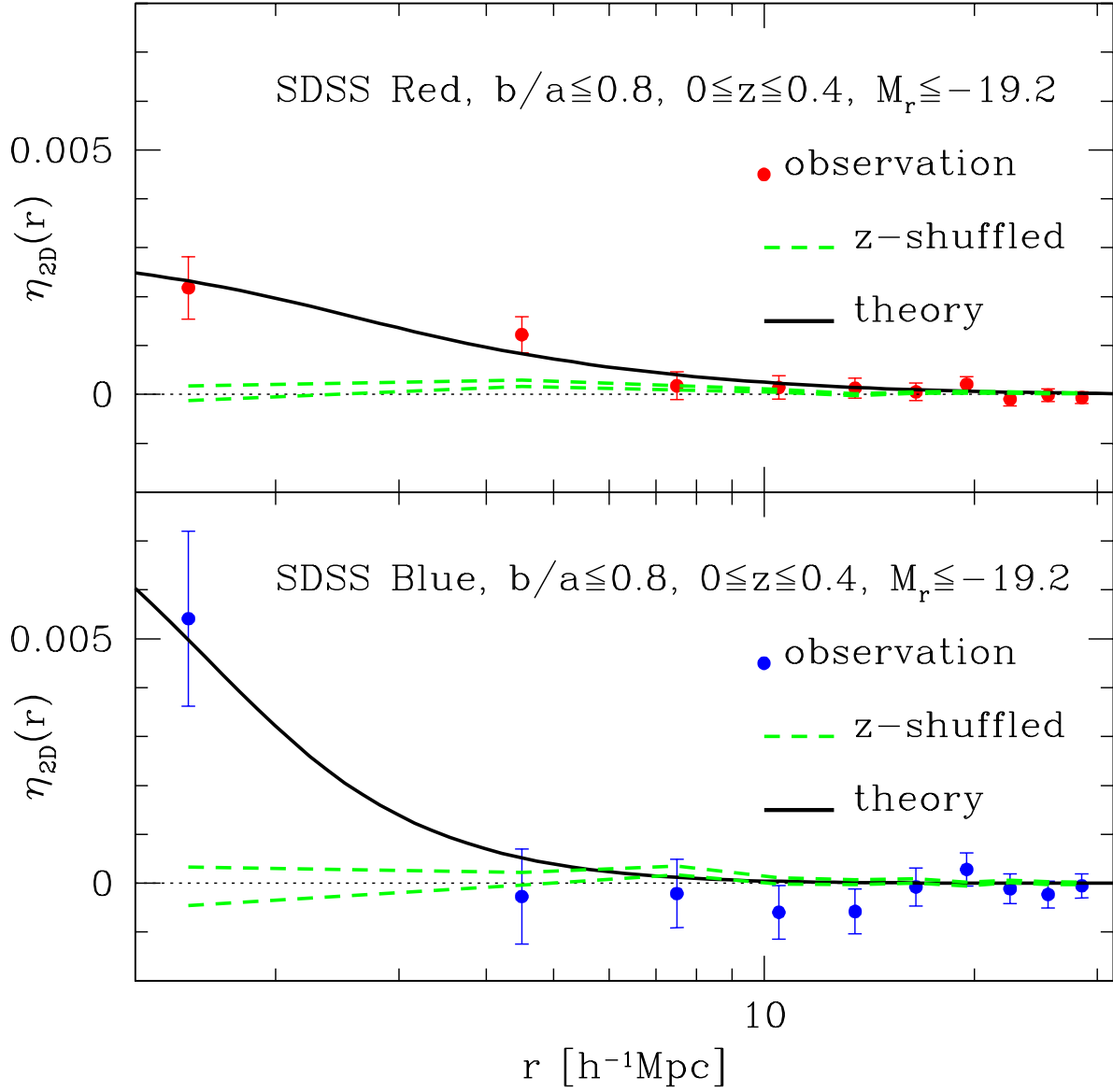


Fig. 1.— Correlations of the two dimensional projected ellipticities from the SDSS red and the blue galaxies (top and bottom, respectively) with the absolute magnitude cut of $M_r \leq -19.2$ in the redshift range of $0 \leq z \leq 0.4$. In each panel, the solid dots represent the observed signals, while the solid line corresponds to the analytic model with the best-fit parameters (eq.[2]) found through χ^2 -minimization. The dashed line corresponds to the correlation from the data with z -shuffled. For the observed signals, only those galaxies with major-to-minor axis ratio of $b/a \leq 0.8$ are considered.

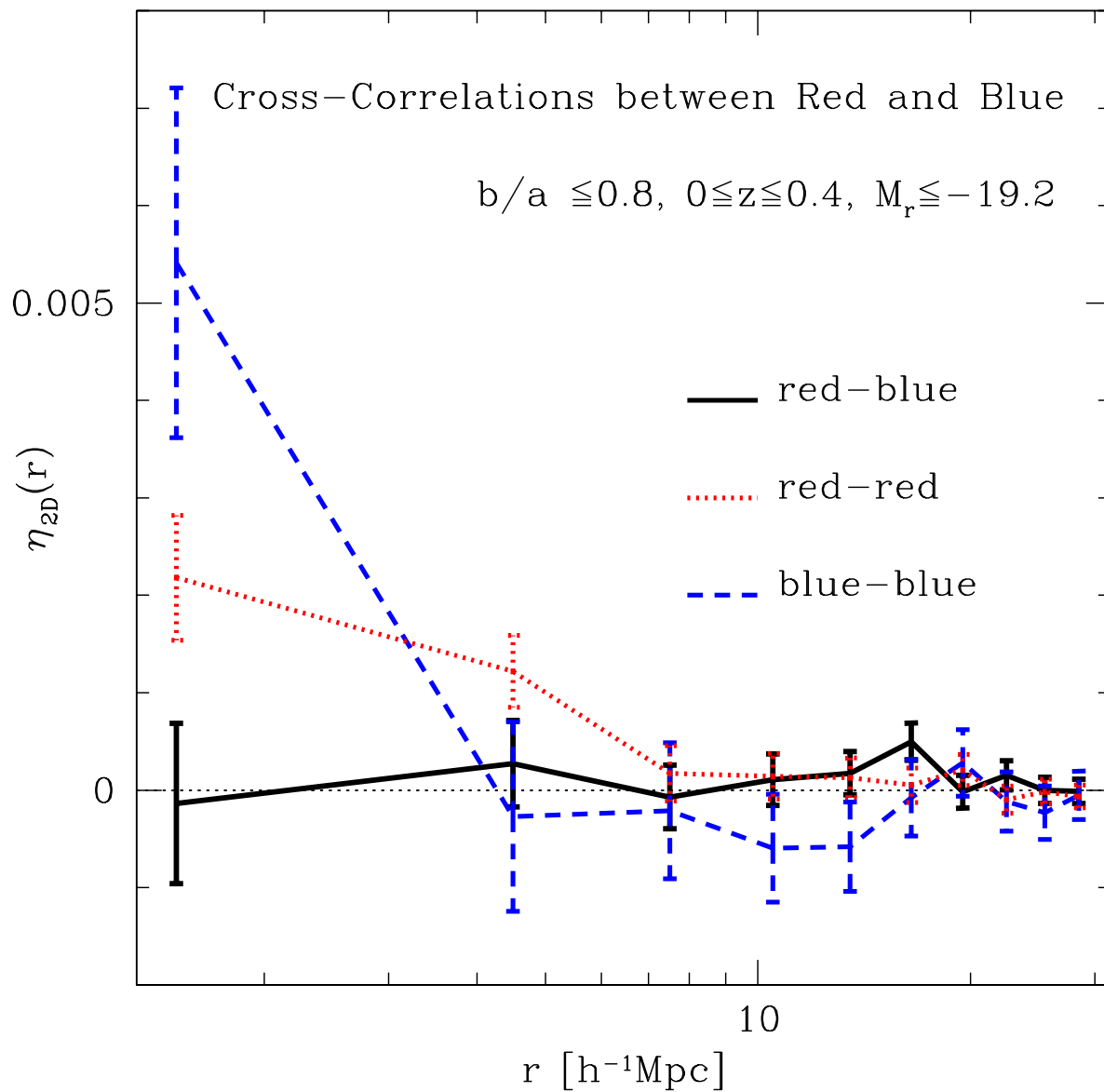


Fig. 2.— Cross-correlations of the two dimensional projected ellipticities between the SDSS red and the blue galaxies (solid).